ON THE MAXIMUM INTENSITY OF HURRICANES

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ABSTRACT

The minimum pressure that can occur within a hurricane is related to the temperature of the sea surface over which it moves. This is done by making certain assumptions and synthesizing an eye sounding, which is used to compute the lowest pressure of the storm. The validity of the computed sounding is tested on eight hurricanes. A series of composite 200-mb charts is constructed from five of the eight hurricanes which reached great intensity to show one synoptic situation which results in maximum deepening. These are contrasted to a similar series of composite charts prepared for storms which reached only minor intensity.

1. Introduction

The principal source of energy of the tropical storm is the release of the latent heat of condensation. The air ascends almost moist adiabatically over a wide area, so that there is little entrainment of drier or cooler air within the inner portions of the storm. Byers [2, p. 431], for example, compared the hurricane to "one huge parcel of ascending air," and this model has been verified by subsequent dropsonde observations [6] from reconnaissance aircraft, which show lapse rates very close to the moist adiabatic. The energy released by parcel ascent from the surface to the upper troposphere is enormous, but only a small portion is converted into kinetic energy. Riehl [9, p. 322] estimated that not more than 15 to 20 per cent of the total energy released by parcel ascent is needed to maintain the hurricane circulation. A large portion of the heat released is, of course, needed to maintain convection in an atmosphere in which lapse rates are much closer to the moist than the dry adiabatic. The rest is spread out over a large area as sensible heat, much of which finds its way into the middle latitude regions.

Two factors combine to limit the amount of energy released by parcel ascent, vast though it is. These are the initial equivalent potential temperature of the ascending air and the prevailing lapse rate within the free atmosphere. The temperature and moisture content of the surface air are closely related to the temperature of the underlying water surface. In this way the ocean temperatures limit the amount of energy available from parcel ascent for both hurricane formation and maintenance.

Palmén [8] showed that in the mean if the surface air at Swan Island were lifted, it would be much warmer than the mean sounding for September up to about 160 mb, while in February the lifted air had about the same temperature as the surrounding air. Thus the amount of energy realized by parcel ascent is much greater during the warmer months. Palmén related the energy available to the water temperatures and concluded that in the mean tropical storms do not form over oceans having water temperatures less than about 26–27C. This limit seems to be rather critical.

The lowest pressure that can occur within a hurricane, as well as the process of formation, may also be related to the water temperatures in the following way. The tropical cyclone possesses a warm core, which means that the intensity of the circulation decreases with elevation, and at some great height, usually above 10 km, the presence of the cyclone can no longer be detected, *i.e.*, the pressure gradient observed at sea level has disappeared, or may even be reversed. If one assumes hydrostatic equilibrium, the minimum possible pressure at the surface is dependent upon the maximum possible mean virtual temperature that can exist within the column extending from sea level to the top of the hurricane vortex and upon the pressure at the top of the column. An attempt will be made to show that the mean virtual temperature within the column is partly dependent upon the water temperature over which the hurricane moves. Consequently the minimum possible pressure at the surface is determined by: 1. the sea surface temperature; 2. the relative humidity of the surface air; 3. the prevailing lapse rates within the area of the storm, and 4. the distribution of the constant pressure heights at the upper levels, *i.e.*, the height and potential temperature of the level from which air can drop into the eye, at the top of the hurricane vortex.

2. The hurricane model

The temperatures attained in the upper atmosphere, following ascent from the surface, are dependent upon the initial surface conditions, *i.e.*, temperature, pressure, and relative humidity, and upon the entrainment of cooler or drier air from outside the hurricane vortex. The latter is highly significant within the outer edges of the storm. It appears unlikely, however, that there is any great amount of entrainment of drier air within the inner portions of the cyclone. Otherwise the observed lapse rates would not be so close to the moist adiabatic. Riehl [9, p. 146] has pointed out that the effectiveness of entrainment in reducing the buoyant energy inside an ascending current will depend upon the width of the current. As the width increases the core of the ascending air becomes more protected from the influences of the environment. Thus a central portion of the ascending current may have higher temperatures and larger updraft speeds than the bulk of the current. It was pointed out in the previous section that within the hurricane, air ascends nearly moist adiabatically over a wide area. Thus the core of the ascending current is well protected from entrainment, and within the inner portions of the storm parcel ascent from the surface to the upper troposphere is very nearly realized. This accounts for the temperature field around the storm. Within the central area, protected from entrainment, are to be found the warmest temperatures, and these decrease outward as entrainment becomes more effective. This temperature field is in accordance with the observed facts.

The temperature field thus produced is warm enough to account for a sizable portion of the pressure difference observed at the surface. However, this warming, relative to the environment, resulting from parcel ascent cannot account for all the pressure fall actually observed within a mature hurricane; consequently additional warming by descent within the eye must be assumed to take place.

The low-level structure of the hurricane consists of a more or less circular eye, possessing a minimum of cloudiness, light winds, and surrounded by a ring of violent winds. The wind distribution has once been assumed [3] to obey a hyperbolic relationship

$$Vr = C \tag{1}$$

outside the eye and a solid rotation

$$V = \omega r$$

within the eye. V is the wind speed, r is the radial distance from the center, ω is the speed of angular rotation, and C is a constant. These simplified velocity profiles are seldom if every observed, however, and various efforts to fit empirical curves to observational data have not been completely successful. The profile due to Hughes [5] is probably the most realistic. He used a modified form of equation (1) in which $Vr^x = C$, and the value of x was determined to be 0.62. Within about one degree of the latitude of the center, however, this relationship overestimates the actual wind speeds. There is apparently not sufficient observational data to establish even approximately the velocity profile for the eye.

Abdullah [1] has presented an interesting hypothesis on the mechanism for development of the hurricane eye. He assumed the wind distribution of equations (1) and (2), and divided the lower layers of the storm into three regions. These are:

1. A subcritical region in which the wind is less than some critical value, defined as the velocity of infinitesimal gravitational waves created at the boundary between two atmospheric layers. This area extends from the "critical radius" outward and thus makes up the major portion of the hurricane.
2. A super-critical region in which the wind velocity exceeds the critical value. It lies within the subcritical region and outside the eye.
3. The eye or innermost portion of the storm.

Abdullah does not discuss the incipient stage of hurricane development in any great detail. However, hurricanes usually form only on pre-existing disturbances, *e.g.*, easterly waves, shear lines, or the intertropical convergence zone, to name a few. These disturbances serve as a sink in the hydrodynamical sense, and cause the air from the outside to converge into the disturbed area. If this convergence persists on a rotating globe and is associated with an efficient high-level divergent mechanism which is necessary to remove the air that has been lifted from the surface, a vortex circulation will be established. During this phase of development air is actively drawn into the core of the developing storm.

The immature stage is identified by Abdullah as the final shape which the storm acquires as a result of the genesis, or incipient phase. It is a steady form which is approached by the storm because of the persistence of the simple vortex circulation. During this stage the eye is the prohibited region into which air from the lower layers cannot penetrate. It must, therefore, be filled with air which has descended from above. However as the hurricane reaches maturity the radius of the eye becomes identical with the critical radius of the immature stage. During the transformation process, air from the lower regions of the circulation is now permitted to flow into the eye and mix with that of the immature eye. Thus the mature eye is filled with a mixture of air, part of which has descended from the upper portion of the vortex and part of which has flowed in from the main body of the hurricane circulation.

As the hurricane deepens the circulation extends to higher and higher elevations. Thus the depth of the prohibited region into which air from the main body of the circulation cannot penetrate also increases. This implies that during the deepening stages of a hurricane the level from which air has descended within the eye also rises. During the early stages air may be drawn in through a deep layer from the upper portion of the vortex, with the level of inflow stabilizing at higher levels as the storm matures.

Observational data can be cited to offer some support to this model. Jordan [7] has recently compiled some mean eye soundings which indicate a mean relative humidity and temperature of 45 per cent and 5.1C at 500 mb for intense storms as compared to 70 per cent and −0.4C for moderate storms. Both the lower humidity and higher temperature within the intense hurricanes are required from a hydrostatic standpoint, but they also suggest descent from a higher elevation than was apparent within the moderate storms. The high humidity inside the eye can perhaps also be taken as evidence of mixing into the eye from the outside.

Such lateral mixing, however, implies the transfer of angular momentum into the eye. This has not been observed, and can be possible only in case the transfer is accomplished slowly and in small amounts so that it can be dissipated by frictional and pressure gradient forces. Jordan [6] earlier suggested two alternate possibilities for transferring moisture into the eye. First, he suggested that perhaps the eye boundary has a shallow slope so that the surface eye is small in comparison with the eye at higher elevations; or it might be postulated that the eye need not extend to the surface at all, so that the clouds usually observed within the lower portions of the eye could be placed below the eye boundary within the storm circulation. Jordan rejected this hypothesis, however, and since his most recent data [7] indicate mean relative humidities of 75 per cent at 500 mb inside the eye of weak storms, 70 per cent for moderate storms, and 45 per cent for intense hurricanes, it must be concluded that he was correct in refusing to accept this possibility. Second, it could be argued that the same air stays within the eye, and that the moisture is introduced by turbulent exchange and evaporation from the ocean surface, and by descent from relatively low levels during the early stages of the storm. This would require, Jordan pointed out, that the resultant wind within the eye have a velocity equal to that of the storm, and there is no evidence to indicate that the wind within the eye shows any persistent or favored direction. Since neither hypothesis appears reasonable, both are rejected, and mixing from the outside is invoked to explain the moisture transfer to the eye. This leaves the question of the transfer of angular momentum an unanswered one.

It can also be postulated that subsidence within the eye need not extend uniformly down to the surface, and this may be used to explain differences in relative humidities Jordan [7] found to exist between moderate and intense storms, *i.e.*, subsidence is stronger and extends to lower levels in intense than in either moderate or weak storms. This will be taken into account in developing a method for synthesis of the hurricane eye sounding.

Returning again to Jordan's [7] mean data for the hurricane eye, the 500-mb temperature of 5.1C would require descent from near the 300-mb level, assuming that the temperature at the time descent began was equal to that of the tropical standard atmosphere for 300 mb. However, if no moisture were added to the descending air, the relative humidity at 500 mb would have to be less than 10 per cent. The actual mean was 45 per cent. This also suggests that mixing from the outside probably occurred during descent.

In his earlier report Jordan [6] cited a famous case, observed by Simpson [10], in which a dropsonde was released within the eye of a mature typhoon whose central pressure was about 900 mb. The 500-mb temperature was 16C, the warmest ever observed at that level. Jordan showed that this temperature would have required dry adiabatic descent from 200 mb, and that if descent began near 100 mb, the average rate of warming would have been about 8C per km. He concluded, therefore, that the record temperature of 16C at 500 mb is probably possible.

Summarizing the foregoing indicates that any effort to compute the temperature structure of the eye of the hurricane should take into consideration the following:

1. Warming by subsidence within the eye must take place, because no other atmospheric process can account for temperatures high enough to explain the low pressures in the eye and the strong pressure gradients around the center.
2. Within deep and mature hurricanes descent within the eye must take place from high elevations (within the 200 to 100-mb range) in order to explain the high temperatures that have been observed at mid-tropospheric levels.
3. Mixing probably occurs between the eye and the hurricane circulation because the relative humidities inside the eye are too high to be explained in any other way. It was indicated previously that the level of inflow into the eye is perhaps relatively low during the early stages of hurricane development, and that this level extends to progressively higher elevations as the storm matures, which it must do in order to account for the high temperatures actually known to occur within the eye. The low level of inflow could account for the high relative humidities within the lower portions of the eye, at least during the early stages of the storm. However, for the relative humidity to remain high after the storm matures and the level of inflow stabilizes at higher elevations would require (in the absence of any mixing into the eye from the outside) that air initially drawn into the eye from low levels remain inside the eye. This possibility has been rejected previously, although it cannot be denied that a small portion of the air inside the lower portions of the eye could possibly remain there throughout the life of the hurricane. An alternate possibility is to assume that air continues to flow into the eye from relatively low levels even after the storm reaches maturity; this would however produce the same result as lateral mixing through the walls of the eye.

If descent within the eye from the 200- to 100-mb range is accepted as a necessary part of the process of the development of a major hurricane, and if the air that was initially drawn into the eye from the lower levels during the early stages of development is not permitted to remain within the eye throughout the life history of the storm, two alternatives exist for replacing the air that is lost from the eye to the outside. First, continued descent from the middle or upper troposphere on down to very near the surface could occur. This would result in temperatures far in excess of those ever observed, and consequently this possibility must be rejected. Second, mixing into the eye from the outside could occur; this latter process results in both reasonable eye temperatures and relative humidities. Thus, mixing must be favored over the first alternative.

3. Synthesis of the eye sounding

The synthesis of the eye soundings used in estimating the minimum pressures within hurricanes was based on the following somewhat arbitrary assumptions. The model for the formation of the hurricane eye, which these assumptions imply, must be considered tentative in nature; also, it is not contended that this model is the only one which results in reasonable eye soundings. It is, however, in fundamental agreement with the models of both Abdullah [1] and Jordan [6], [7].

a. After the hurricane has reached its maximum intensity the primary inflow into the eye takes place from the upper portions of the vortex. Below 10 km some inflow is permitted through the wall of the eye, due in part to lateral mixing and in part to the expansion of the eye during the transformation of the immature eye to the mature stage. This mixing process does not account for the lack of transfer of angular momentum into the eye, or rather it assumes that if such transfer takes place it does so in small increments and at such a slow rate that it can be dissipated by frictional and pressure gradient forces. Whether or not this actually occurs, however, cannot at the present time be determined.

b. The temperature at the level where descent began is assumed to be that which would be produced by moist adiabatic ascent from the surface. This is an overestimate of the actual temperature, since entrainment and mixing with environmental air tend to reduce the actual temperatures to be found at the upper levels. The amount by which the upper temperatures are reduced by these processes cannot be determined.

c. The air within the eye is 100 per cent subsided air from the top of the vortex down to 10 km. Below that level the descending air mixes with saturated air from the hurricane circulation in accordance with the following empirical relationship:

$$M_0 = 15 + 3.5z + 0.5z^2 \qquad (3)$$

for values of $z \leq 10$ km. M_0 is the parts per hundred of descended air within the eye and z is the elevation in km. This relationship was determined by assuming various ratios of dry subsided air and saturated air from the hurricane circulation until a mixture was obtained that gave both realistic eye soundings and reasonable surface pressures. Equation (3) was the most satisfactory although there is no reason to assume that this combination is unique. Examination of equation (3) shows that it possesses the following features:

1. At 500 mb the eye is composed of about 50 per cent subsided air and 50 per cent saturated air, which would result in a relative humidity of about 50 per cent for that level. This is in good agreement with the mean data for intense storms as compiled by Jordan [7].
2. At the surface the eye is composed of 85 per cent saturated air (about 85 per cent relative humidity), which is again in good agreement with the results of Jordan.
3. The overall volume ratio for that portion of the eye below 10 km is about equal portions of subsided air and saturated air from the hurricane circulation. This volume ratio is in agreement for Abdullah's [1] model for the mechanism for the formation of the hurricane eye.

Obviously not all hurricanes possess the same eye structure in regard to either temperature or relative humidity both of which are to a certain extent a function of the intensity of the storm (or perhaps it is the other way around), with the eye of the intense storms being both warmer and drier, and this fact is well illustrated by the mean data of Jordan [7]. Equation (3) results in eye soundings with a moisture distribution almost identical with the mean for the more intense storms. It should therefore probably be considered as more representative of intense than of moderate or weak hurricanes. Equally obvious is the fact that no simple computational procedure as that employed in synthesizing the eye sounding can hope to duplicate the complicated structure of the actual eye soundings. The best that can be expected of it is a rough approximation of the mean virtual temperature for the eye.

d. The temperature of the surface air before ascent began was assumed to be that of the sea water, the relative humidity was about 85 per cent, and ascent began at 1010 mb. This is approximately equivalent to a lifting condensation level of 970 mb. One important consideration that has not been taken into account is the transfer of sensible heat from the turbulent ocean surface to the air spiraling inward towards lower pressure, a phenomenon that has been noted by both Byers [2, p. 432] and Riehl [9, p. 286]. If isothermal expansion and a corresponding increase in mixing ratio from a pressure equal to the lifting condensation level to the center of an intense hurricane with a central pressure of 900 mb are assumed, the error [9, p. 286] would be appreciable. However, neither the pressure at which ascent began nor the

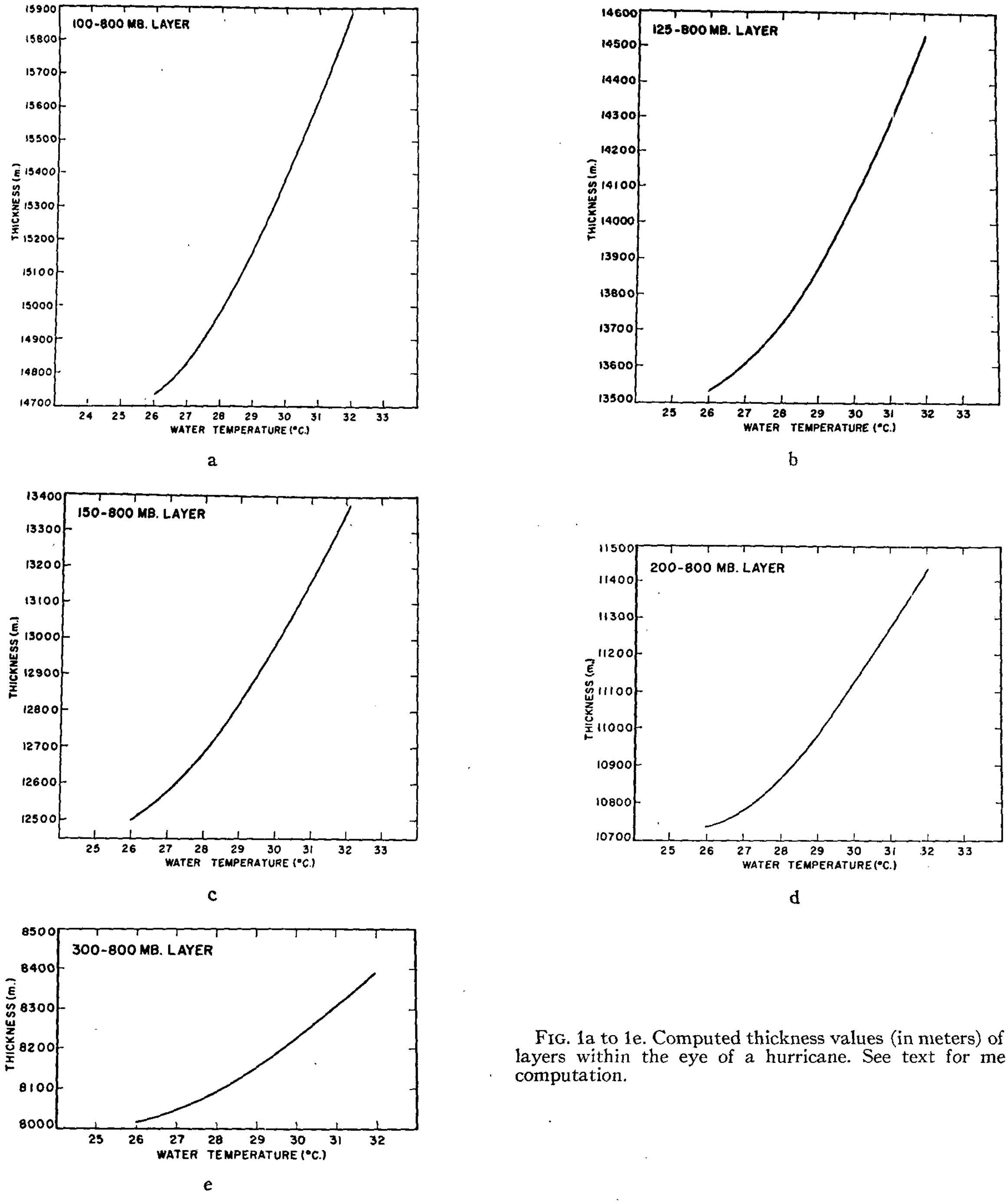


FIG. 1a to 1e. Computed thickness values (in meters) of various layers within the eye of a hurricane. See text for method of computation.

amount of sensible heat supplied by the ocean can be accurately determined for individual storms. On the other hand, ascent takes place over a wide area, at pressures ranging from near 1010 mb to that occurring within the center of the storm, and if the lifting condensation level of 970 mb represents the mean pressure at which the saturated air began its ascent, and this may be the case for hurricanes of moderately large size, then assumption (4) may be approximately correct.

With use of this model for the eye formation, eye temperatures were computed by an iterative process at 1-km intervals from the top of the vortex down to the surface. Descent from various levels ranging from 100 to 300 mb was assumed. Thickness values of 100-mb layers were determined, and by working down the thicknesses of the several layers from the top of the vortex down to 800 mb were calculated. These were expressed as a function of the sea-surface temperature. The results are shown in fig. 1. From the known heights of the constant-pressure heights near the top of the vortex, the height of the 800-mb surface was determined. This height in turn was converted into a sea-level pressure by the use of table 1.

TABLE 1. Surface pressure (P_c) in millibars *versus* 800-mb height, H, in meters. T_v is the mean virtual temperature of the column from the surface to 800 mb.

H 800 mb	$P_c(T_v = 25C)$	$P_c(T_v = 30C)$	$P_c(T_v = 35C)$
500 m	847 mb	846 mb	845 mb
600 m	857 mb	856 mb	855 mb
700 m	867 mb	866 mb	865 mb
800 m	877 mb	876 mb	874 mb
900 m	887 mb	886 mb	884 mb
1000 m	897 mb	896 mb	894 mb
1100 m	908 mb	906 mb	905 mb
1200 m	918 mb	916 mb	914 mb
1300 m	928 mb	926 mb	924 mb
1400 m	939 mb	937 mb	935 mb
1500 m	950 mb	947 mb	945 mb
1600 m	961 mb	958 mb	955 mb
1700 m	972 mb	969 mb	966 mb
1800 m	983 mb	981 mb	977 mb
1900 m	995 mb	991 mb	988 mb
2000 m	1006 mb	1002 mb	999 mb

This process is designed to produce realistic eye soundings, at least from the surface up to about 500 mb; above that level little data are available with which to compare the synthetic soundings. Fig. 2 shows computed eye soundings and an actual eye sounding. Curve "A" is the dropsonde made within the typhoon in which the 500-mb temperature of 16C was observed. Curve "B" is a computed eye sounding based on a water temperature of 86F. The latter curve is the one used to compute the minimum pressure in Hurricane Janet, 1955, which prior to intensification moved over a water surface having a temperature of 86F. The computed minimum pressure was 915 mb, and the reported minimum was 914 mb. The lowest reported within the typhoon to which curve "A" pertains was about 900 mb.

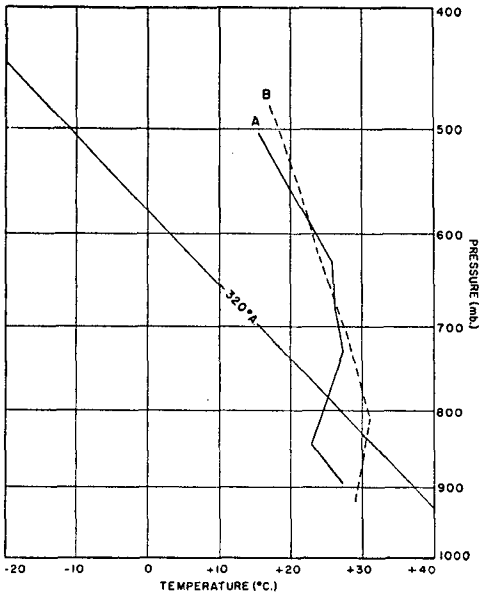


FIG. 2. Computed eye sounding based on a water temperature of 86F, Curve "B" and an eye sounding made within a typhoon [10], Curve "A".

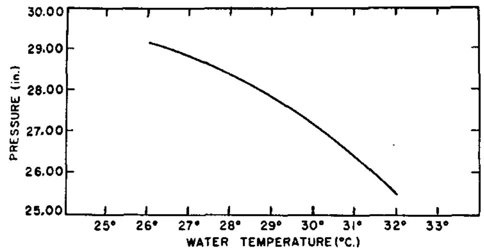


FIG. 3. Minimum probable pressure within a hurricane over various sea-surface temperatures.

Fig. 3 shows the minimum probable pressures for various sea-surface temperatures, based on computed eye soundings, assuming that the top of the vortex is at 100 mb and that the height at that level is equivalent to the tropical standard atmosphere. The range extends from 29.15 in (987 mb) at 26C, below which temperature Palmén [8] believes that hurricanes do not form to 26.35 in (892 mb) at 31.1C (88F). The latter pressure is the lowest ever recorded in the Western Hemisphere and occurred in the famous Florida Keys hurricane of September of 1935. Water of 86F occurred over a wide area in the Caribbean in September, 1955, and while 88F is an extreme value, it does not seem beyond the realm of possibility that temperatures approaching that value could have occurred over a limited area at the time of that violent hurricane. It is probably more realistic, however, to assume that less mixing into the eye from the outside occurred than would be indicated by equation (3). This would permit a somewhat lower pressure for a given water temperature than that obtained from fig. 3.

It is not suggested or intended that fig. 3 will be expected to give, except under ideal conditions, a close estimate of the actual minimum pressure within an individual hurricane, because obviously circulation features and not the water temperatures are the dominant features in determination of the intensification process. It is, however, suggested that normally fig. 3 will yield a pressure below which it is safe to assume the actual pressure will not fall.

4. Computation of minimum pressures for individual hurricanes

To test the validity of the process of constructing eye soundings and estimating the minimum surface pressures by the method described in the previous section, computation of the minimum pressures for eight hurricanes for which both sea-surface temperatures and upper-air soundings were available was carried out. These were: Carol, Edna, and Hazel, 1954; Connie, Diane, Hilda, Ione, and Janet, 1955. Data from these storms were not used in working out equation (3), and the following computation may be interpreted as an independent test of the process.

The sea-water temperature analyses by Fisher [4]

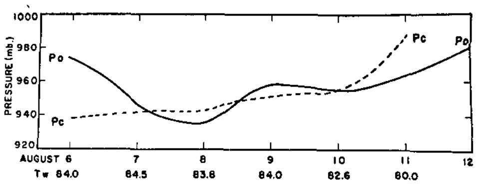


FIG. 4. Calculated minimum probable pressure (P_c) *versus* observed central pressure (P_o) for hurricane Connie, 1955. T_w is the water temperature in degrees F.

were used. Fisher prepared daily water temperature charts, using all available data for each day without regard to the synoptic period of the observations. Isotherms were drawn for intervals of 2F.

To determine the temperature of the surface air entering the storm circulation (assumed to be equal to that of the water), the water temperatures were averaged, weighted according to the areas inclosed by the isotherms, over a circle with a radius of 4-deg latitude, the center of the circle being at the midpoint of the 24-hr motion of the hurricane, the period beginning at 1230 GMT. An upper-air station was selected along or near the projected path of the hurricane, usually outside the circle used in determining the mean water temperature.

The 1500 GMT soundings were used and the highest level to which the rising air could ascend was determined, assuming parcel ascent. This elevation was usually at or near the tropopause and fell within the 200- to 100-mb range. The height of the standard constant-pressure surface at or just below this level was noted and assumed to be the top of the potential hurricane vortex. No corrections were made for the height rises that can normally be expected to occur with the approach of a tropical cyclone. The thickness of the layer from the top of the potential vortex down to 800 mb was obtained from fig. 1, and this was converted into a sea-level pressure by the use of table 1.

These calculations were performed daily for each storm south of 35-deg north latitude. Forty-five calculations were made. The results for Connie, 1955, are shown in fig. 4, which shows the daily values of the calculated minimum pressure (P_c) *versus* the lowest observed pressure (P_0). However, it should be noted that the curve labeled P_0 cannot be taken as an indication of the actual rate of deepening, since the lowest pressure observed each day was plotted at equal intervals, regardless of the time of day at which it was determined. Most of them, however, occurred between the hours of 1500–2200 GMT.

TABLE 2. Calculated minimum pressure (P_c) *versus* observed minimum pressure (P_o) for eight storms.

Storm	P_c	P_o
Carol, 1954	935 mb	960 mb
Edna, 1954	935 mb	940 mb
Hazel, 1954	937 mb	937 mb
Connie, 1955	938 mb	936 mb
Diane, 1955	949 mb	969 mb
Hilda, 1955	930 mb	951 mb
Ione, 1955	939 mb	938 mb
Janet, 1955	915 mb	914 mb

A summary of the calculated and observed pressures for the eight storms is shown in table 2. In five of the eight storms P_c was within 5 mb of P_0. Two of the hurricanes deserve special comment. Diane (1955) formed over relatively warm water and the initial calculation made for 12 August indicated that this storm was potentially one of moderate severity (949 mb). Diane subsequently moved over colder water, and succeeding calculations indicated that the lowest pressure would probably never fall below 962 mb. The lowest observed within this hurricane was 969 mb.

The computations suggest that Hilda (1955) could have been almost as severe a hurricane as Janet. However, Hilda was twice disrupted by passage over land masses. In spite of this fact, it reached a minimum pressure of 951 mb, recorded at Tampico on 18 September. In case of Carol, 1954, other conditions must have been present to prevent intensification, inasmuch as P_c was about 25 mb less than P_0.

In every case there was an appreciable time lag between the occurrence of the computed minimum and the observed minimum pressures. This lag was usually within the 24–48-hr range, although it varied widely. This suggests that the time required for the completion of the cycle, from the inflow at the surface through the outflow in the upper tropopause, and then descent within the core to form the eye is of the order of 24–48 hr, although the range may vary considerably from storm to storm. This may partly explain the failure of Diane (1955) to reach the intensity indicated by the single calculation made for 12 August. The storm did not remain over warm water long enough. In estimating maximum intensity the future course of the storm as well as the temperature of the water over which it is expected to move must be considered.

These computations seem to suggest that the maximum intensity a hurricane may be expected to reach is partly dependent upon the water temperature over which the storm moves. It should be emphasized, however, that the water temperature is only one of several factors which contribute to intensification and that these other factors are of at least equal importance, quite possibly more so. Among these other factors are:

a. Features of the field of motion existing in the lower and middle troposphere in the vicinity of the storm, notably the presence of cyclonic vorticity.

b. Temperatures within the upper troposphere, which are related to the field of motion, are probably as significant as the sea-surface temperatures in determining lapse rates and the available convective energy.

c. The relative humidity within the lower air layers, which can be significantly variable even with the same sea-surface temperatures, depending on the strength and curvature (cyclonic versus anticyclonic) of the lower wind field.

d. The presence or absence of an efficient high-level outflow mechanism, which is necessary to remove the air that has been lifted from the surface. Otherwise air will accumulate within the upper portions of the storm area and the storm will not deepen.

5. Circulation influences at 200 mb

Five of the eight storms discussed in the previous section apparently reached the maximum intensity that could be supported by the prevailing water temperatures. An examination of the circulation around these storms might therefore be expected to reveal some of the features most favorable to deepening. These five were Edna and Hazel, 1954, and Connie, Ione, and Janet, 1955. These storms also possess the common feature of having reached approximately the same lowest pressure at some time during their histories.

As is frequently the case when analyzing meteorological data in tropical areas there were not sufficient data to permit the preparation of detailed analyses for individual storms. Accordingly a series of composite charts was prepared for the 200-mb level; these were prepared for a four-day period, D − 2 through D + 1. The day the minimum pressure was reached was designated as D-day. The average central pressure for the five storms for the four-day period are shown in fig. 5.

In two cases some subjectivity entered into the determination of D-day. A pressure of 914 mb was recorded (Janet, 1955) at Chetumal, Mexico, about 0700 GMT, 28 September; D-day was accordingly determined to be the 27th, with about the same minimum pressure seeming likely. As for Hazel, a pressure of 974 mb was measured by aircraft at 0045 GMT 14 October. No further central pressures were obtained within this severe hurricane until the storm passed inland near Myrtle Beach, S. C., around 1400 GMT 15 October, when a pressure of 937 mb [11] occurred. Intensification apparently took place rapidly during the night of 13 October and early morning of the 14th, and so D-day was designated as the 14th, and a central pressure equal to that occurring as the center moved inland was assumed.

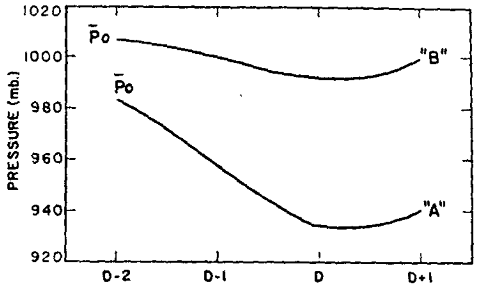


FIG. 5. Mean daily central pressure for five major hurricanes (Curve "A") and four minor hurricanes (Curve "B").

TABLE 3. Number of observations, by quadrants, used in the preparation of the composite charts of fig. 6. D-day is the day of maximum intensity.

	Quadrant			
Day	NE	NW	SW	SE
D − 2	7	76	24	10
D − 1	21	96	29	10
D	31	120	47	15
D + 1	39	84	61	19

The composite analyses were prepared in the following way. All available upper-air soundings, 0300 GMT, 1500 GMT, plus any special hurricane soundings that were made, were plotted daily for each individual storm. The area plotted covered a grid extending 32 deg of latitude in an east-west direction and 20 deg of latitude in a north-south direction. The surface position of the hurricane was at the center of the grid, and the grid moved with the storm. The data for the individual storms were analyzed carefully, leaning heavily on continuity. The over-all analyses were considered reasonably accurate, although there were not enough data to reveal minute details. Table 3 shows the number of observations, by quadrants, that went into the analyses. The heights were read from the individual storm analyses at the centers of squares of 2 deg of latitude. The composites were prepared from the mean data.

The series of composite charts pertaining to the five intense storms listed above (Case I) is shown in fig. 6. Several features are prominent and may be significant. They are: 1. The presence of the large anticyclone to the east of the center of the hurricane; 2. The trough to the northwest; and 3. The anticyclone to the southwest. These features are persistent throughout the four-day period.

If the synoptic situation indicated by the charts of fig. 6 is really responsible for the deepening of the storms, and this possibility is suggested although that such is the case is by no means certain, the salient features listed in the preceding paragraph are subject to the following interpretation: The combined action of the high to the east and the trough to the northwest furnishes an efficient outflow mechanism for the evacuation of the vast quantities of air that have been lifted from the surface. The high to the southwest apparently causes a part of the air entering the system from the west to be diverted around its borders to the southwest, *i.e.*, it does not enter the hurricane circulation. The result is quite probably net divergence, although without a detailed knowledge of the wind field, this cannot be established quantitatively. In the region immediately to the north and northwest of the surface center, the individual 200-mb analyses

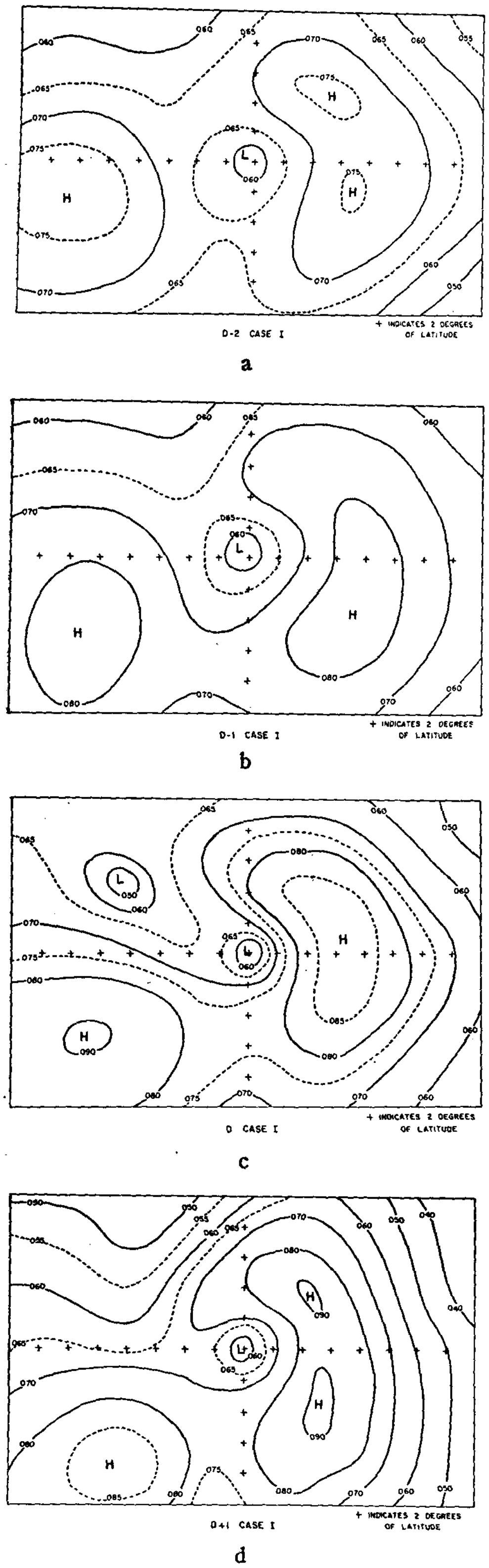


FIG. 6a through 6d. Composite 200-mb charts of five major hurricanes. D-day is the day the lowest pressure was observed.

showed a remarkable tendency for cross contour flow, amounting at time to almost 90 deg. The magnitude of this flow as it pertains to the composite charts, however, cannot be estimated with any degree of accuracy.

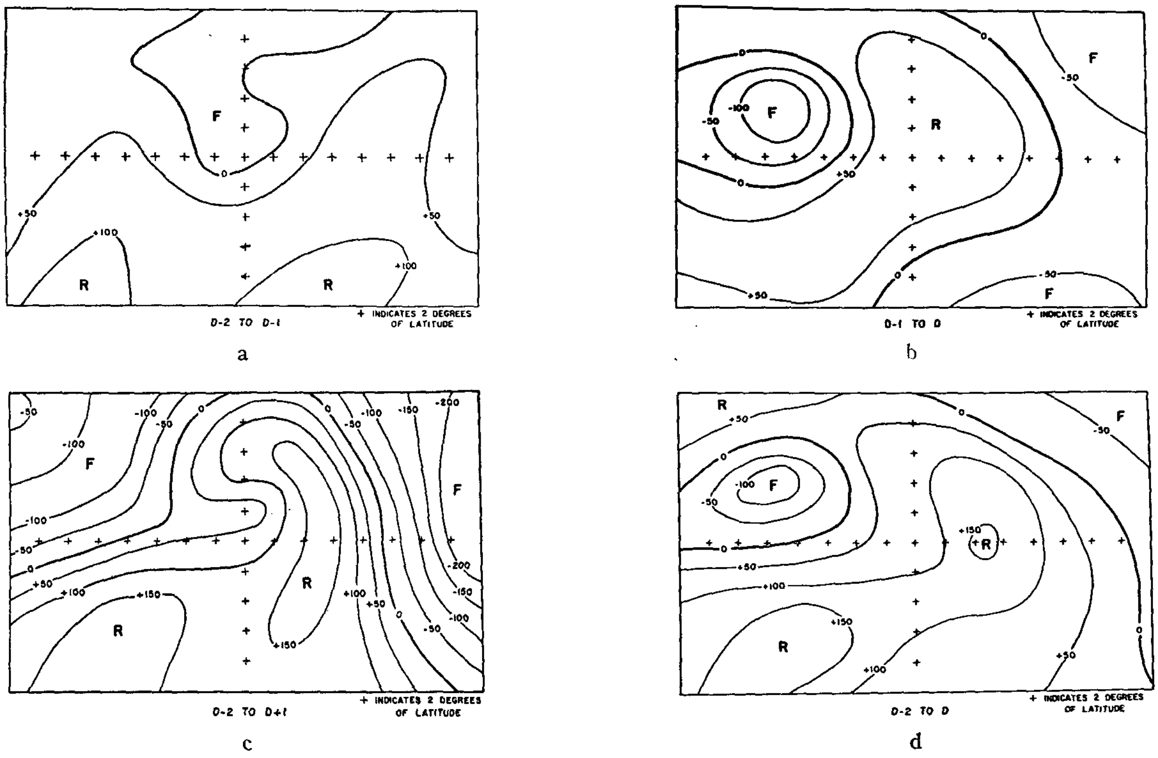
An examination of the composite charts for the four days shows that the storm has maintained approximately the same position relative to the two anticyclone centers and the trough for the entire period. The high to the southwest has shifted slightly to the south as the center of the storm moved to a more northerly latitude. By D + 1 there appears to be a somewhat lesser tendency for the westerlies to be diverted around the southwestern high pressure area. In fact there is some indication that the flow is more into the center of the high-level vortex, which may be one reason for the beginning of the filling process.

The D + 1 chart reveals a strong northerly flow to the east of the storm. This has been observed in several individual hurricanes at the 200-mb level. There is a strong possibility that this is a result of the intensification process and that by this mechanism the lifted air finds a return channel to the tropics.

There is an obvious alternate interpretation. Fig. 5 shows that even on D − 2 the mean pressure for the group of intense storms was about 982 mb, *i.e.*, the individual storms were already well developed hurricanes. It is just as logical, possibly even more so, to assume that the development of the two upper-level anticyclones is a *result* of the deepening that has already done on prior to D − 2 instead of the *cause* of the deepening that occurred subsequent to D − 2. Many will undoubtedly prefer the alternate interpretation. Unfortunately, the question must remain an open one, inasmuch as there were not enough data to permit the preparation of composite charts for any time prior to D − 2, *i.e.* for D − 3, D − 4, *etc.* The presence of the trough to the northwest, however, is not subject to an alternate interpretation since it is apparently a part of the middle latitude circulation.

The 200-mb height changes for 24- to 72-hr periods are shown in fig. 7. From D − 2 through D + 1 there was a gradual intensification of the anticyclones and a deepening of the trough. However, most of the changes occurred during the period D − 2 through D-day. The combined effect of the height rises to the east of the storm and the falls to the northwest increases the east-west gradient to the north of the center. This in turn intensifies the outflow. The rises to the east are quite likely a result of the hurricane, although the same cannot be said of the falls to the northwest, and to this somewhat limited extent the hurricane provides a portion of its own high-level outflow mechanism, once the circulation is well established. Another feature that shows up in both the 200-mb charts and the height-change charts is the nose of the high protruding ahead of the hurricane vortex.

If the prominent features of the composite charts of Case I are really important to the deepening process, a similar series prepared from storms which did not reach major intensity might be revealing. Four storms



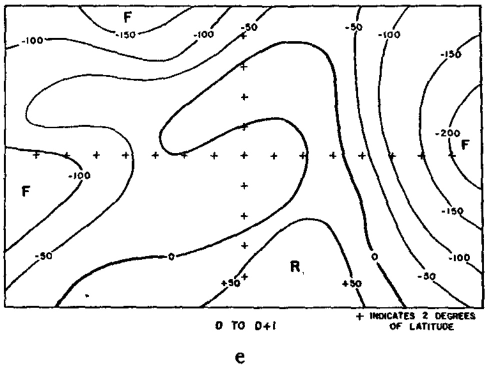


Fig. 7a to 7d. 200-mb height changes in feet, based on the data from the composite charts in fig. 6.

in this category were selected. They were Item, 1951, Able, 1952, and Barbara and Dolly, 1953. The mean daily pressures for these storms are shown in fig. 5. All were of hurricane intensity at some time during their histories, but the central pressures within none of them fell below about 987 mb.

A second set of composite 200-mb charts was prepared from data from these minor hurricanes (Case II). These were prepared in the same manner as were the composite charts for Case I except that only 0300 GMT and 1500 GMT data were used, no intermediate soundings being available; these are shown in fig. 7.

For Case II the D − 2 chart shows a high to the east of the center of the hurricane and there is some indication of a trough to the northwest, but it is much weaker and farther away from the hurricane than the corresponding trough in Case I. There is no high to the southwest and no evidence of a closed cyclonic circulation over the surface position of the center. This is not surprising, however, since the storms were relatively weak, and even on D-day the mean pressure within the center of the four storms was only 992 mb. There is some slight indication that the high to the east and the trough to the northwest combine to produce a weak outflow mechanism. There is no evidence of air entering the system from the west, but there may be a weak inflow from the south-southeast as a result of the large high to the east.

The situation is roughly similar on D − 1, but by D-day the westerlies have moved southward and the anticyclone to the east has rotated to a more east-west position. The surface center is now located under the northern periphery of the upper level anticyclone, and the inflow from the west now appears to be at least as great as the outflow around the northern border of the high. On D + 1 the features present on D-day are even more pronounced. At this time the storms were beginning to fill.

There is a gradual fall of the constant pressure surfaces over the northeastern quadrant from D − 2 through D + 1, in an area where the heights rose in Case I. The maximum heights observed near the center of the anticyclone to the east are about the same in both cases. This suggests that abnormally great 200-mb heights are not necessarily an antecedent condition for intense hurricanes and that the height rises observed in the northeast and southwest quadrants of Case I are a result of the intensification process.

As in Case I the composite charts of Case II are subject to two interpretations, *i.e.*, the lack of similarity between the charts of Case I and Case II may indicate either the *lack* of development of the storms of Case II or the *reason* for lack of development. With the data at hand, however, the question cannot be resolved.

6. Conclusions

The minimum pressure of the hurricane is related to the temperature of the sea surface over which it moves, and there is some evidence that this relationship can be expressed on a quantitative basis. The circulation features around the storm, however, may prevent the pressure within a tropical storm from reaching its potential minimum, *i.e.*, warm water temperatures are a necessary but not a sufficient requirement for major intensification. It also appears that for the pressure to fall to the minimum value indicated by the water temperature the storm must remain over the water surface for at least two days.

The 200-mb circulation characteristic of major intensification appears to be: 1. A major anticyclone to the east of the storm, 2. A well-developed trough to the northwest, and 3. An anticyclone to the southwest. These positions are relative only; the mean motion of the storms used in the preparation of the composite charts was towards the northwest. For storms moving in other directions the positions of these salient features of the 200-mb flow should be shifted accordingly. These features combine to produce the maximum outflow from the area of the storm, while the inflow is reduced to a minimum. Deepening is accompanied by intensification of the eastern anticyclone, and in the absence of height rises to the west or northwest (or in the presence of height falls within these regions) the outflow is increased. Thus an intense storm to some extent may be capable of increasing its own high-level outflow mechanism. Intensification is also accompanied by an increase in the northerly flow to the right of the anticyclone to the east, thus providing a channel for the return to the tropics of a portion of the air that was lifted from the lower levels during the deepening process.

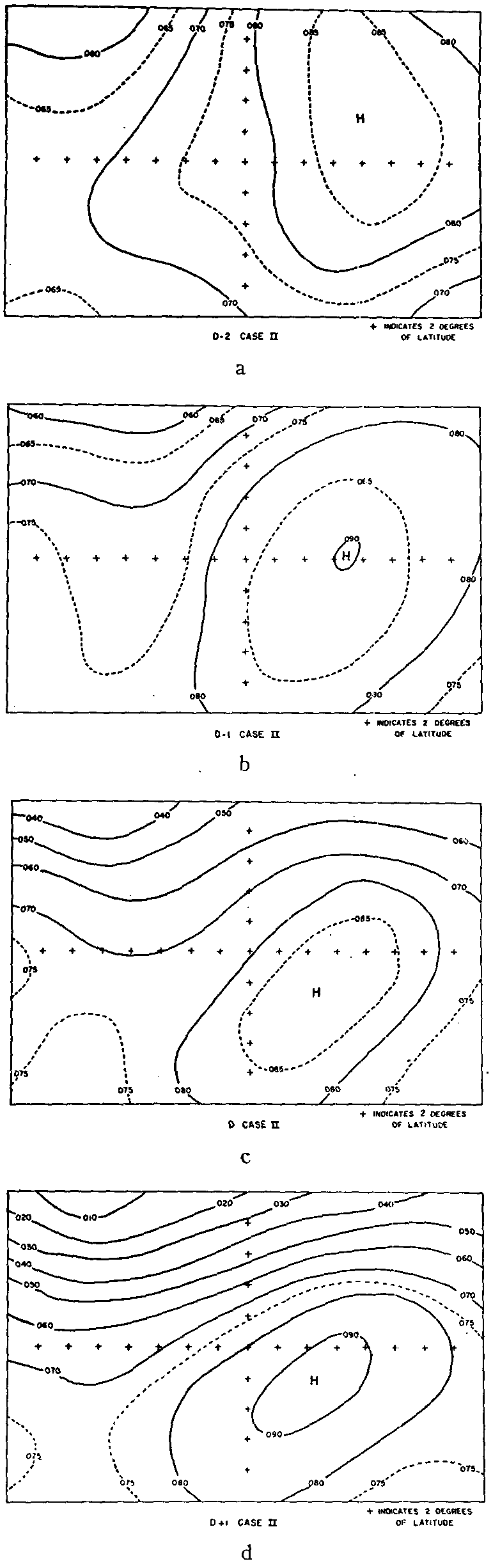


FIG. 8a to 8d. Composite 200-mb charts of four minor hurricanes. D-day is the day the lowest pressure was observed.

It is suggested that the 200-mb circulation described in the preceding paragraph is typical of the synoptic situation leading to major intensification. There is, however, an equally logical alternate conclusion. An examination of fig. 5 shows that the average central pressure for the major storms was already lower on

D − 2 day than for the minor storms on D-day. It may be argued, therefore, that the two sets of composite charts merely illustrate the differences between two storms of different intensity, one well-developed and one poorly-developed, and not the difference between two synoptic situations, one leading to development and the other to nondevelopment. This may be true. Obviously the limited number of cases presented cannot be considered as proof of the hypothesis expressed in this paper, and the question as to which of the two alternate interpretations is correct must necessarily be left open.

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